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The goal of this project was development of a miniature ArF laser and associated miniature gas handling apparatus. In the first year we improved performance of a waveguide ArF laser by redesigning the microwave power delivery system, quantified the effects of oxygen in the laser discharge, and designed a miniaturized gas supply. In the second year, we developed a miniature ArF laser of more conventional design that produced mW of average power at a pulse repetition rate of 100 Hz.

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FINAL TECHNICAL REPORT

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I. INTRODUCTION

A. Significance of the Project

As a consequence of their strong interaction with most molecular species, far uv wavelengths between 190 and 250 nm find a broad array of applications. Unfortunately, these short wavelengths are relatively difficult to generate. Upconversion of Nd:YAG sources becomes complex and inefficient at wavelengths below the 266 nm fourth harmonic, and uv ion lasers cannot produce significant emission below 260 nm. Frequency multiplied dye and Ti:sapphire sources have been described, but all require two to four wavelength conversion steps to reach the ultraviolet. At wavelengths in the 190 - 250 nm range excimer lasers offer the only practical alternative for most applications.

Typically, excimer lasers are large, complex and expensive and require handling of large volumes of corrosive gas. These characteristics restrict the number of practical applications for excimer lasers and, by implication, for uv lasers in generaal. There is a growing need for small, inexpensive, deep UV sources that have minimal facility requirements.

II. Approach.

In earlier work, Potomac Photonics has developed a small KrF laser at 248 nm based on electrodeless microwave discharge excitation that alleviates some of the size and cost problems associated with conventional KrF excimer sources. As part of the contract effort, we have explored extension of this technology to ArF at 193 nm.

The initial goal of the project was development of a miniature ArF laser capable of at least 25 mW of average power and associated miniature gas handling apparatus. Additional design goals were a long maintenance period and low production cost.

Key development issues at the beginning of the project were:

1. Improvement of the microwave power delivery structure. Computer modelling suggested that reduction of parasitic microwave power losses to the 10% level could increase laser energy by as much as a factor of two.

2. Elimination of oxygen in the gas supply. Oxyfluorides resulting from oxygen in the discharge produce large transcient absorption that reduces output power at high pulse repetition rates.

3. Evaluation of gas supply components and design of a miniaturized supply. Improvement of techniques for analysis of the laser gas.

4. Improvement of operating lifetime.

5. Design for low cost manufacturing.

During the contract period we conducted investigations of micromachining applications of the waveguide ArF laser and began an evaluation of applications in laser refractive surgery in collaboration with a medical laser systems company. This work showed that laser power higher that the initial Phase II design goal of 25 mW would be needed for the laser to find a large market in either area. In both applications processing speed would be severely limited by average power.

An additional complication surfaced in development of the waveguide excimer ArF laser gas supply. We found that oxygen impurity levels as low as 1-2 ppm could produce a significant reduction in laser power. Although gas premixes with the required purity were produced during work with the gas vendor, shelf life of the supply was limited.

In view of these results, it was determined that the second year of the project would be used to pursue an alternative design that would exhibit less sensitivity to gas supply purity and be more easily scaled to higher average powers.

II. TECHNICAL PROGRESS

A. Waveguide ArF Laser Investigations.

1. Microwave power delivery.

The power delivery system was redesigned to reduce mismatch and microwave losses. Encapsulation epoxies were optimized to improve coupling efficiency and minimize dielectric losses. These changes typically increased output energy by more than 50%.

2. Improvement of the operating lifetime.

Extensive lifetesting of waveguide ArF and KrF components has been carried out. Early failure mechanisms involved switching transistors in the power supply electronics and dielectric failure in the high voltage pulse transformer. Redesign of a high voltage amplifier board to include more protection circuitry has essentially eliminated transistor failure, and improvements by the vendor in the winding of the transformer has reduced the frequency of failure.

Discharge tube failures due to dielectric breakdown also have been investigated. Improved fabrication techniques to strengthen bonding between epoxy layers and eliminate voids in encapsulation and have resulted in lifetimes exceeding 500 hours and one billion pulses at high pulse repetition rates. Although the final ArF laser design did not benefit directly from lifetime studies conducted early in the project, our KrF waveguide laser has benefited significantly.

2. Gas supply.

The effect of oxygen impurities has been discussed in detail in the Phase I technical report. In general, oxygen reacts with fluorine atoms produced in the laser discharge to produce transient O_2F and O_2F_2 species with lifetimes of several hundred milliseconds. These species are strongly absorbing at 193 nm. Since gas in the discharge region is exchanged only a few times per second in a waveguide excimer laser, generation of the oxyfluoride species reduces laser pulse energy at high pulse repetition rates.

We have worked with Spectra Gases (Irvington, NJ) to quantify the effect of oxygen in the laser gas and identify oxygen sources in the gas stream. Potomac provided a laser to Spectra for several weeks and worked onsite and offsite with Spectra to investigate the role of oxygen and other impurities detected in the gas supply and laser exhaust stream. Instrumentation available at Spectra included gas

chromatography, long-cell FTIR, and a proprietary oxygen measurment technique. After it was determined that low levels of oxygen could play an important role in laser operation, several laser gas premixes were made and intentionally doped with various oxygen concentrations to verify the analytical data. This portion of the study confirmed that oxygen concentrations as small as 2 ppm could have a measureable effect on the laser energy.

Following the initial work, Spectra provided several test cylinders of high purity ArF premix to Potomac for shelf life tests. These cylinders were tested before and immediately after shipment, and typically contained oxygen impurities in the 1 - 3 ppm range. Although the effect of these impurity levels was measureable, the reduction in laser energy at high pulse repetition rate might have been tolerated if shelf life of the premix exceeded several months. However, even after only 1 to 2 months, laser performance of the gas mixtures suggested that oxygen levels had increased. The increase in oxygen concentration probably is due to fluorination of residual oxides on the cylinder walls.

At this point it was clear that the current state of the art of excimer gas technology probably could not support ArF waveguide lasers if they were made commercially available.

Early in the project we began work on a miniaturized gas supply based on a 1.2 liter storage cylinder and a miniature regulator that is capable of operating a small excimer laser in field instrumentation or surgical applications.

Work on the miniature supply has been completed and a sketch of the supply is shown in Fig.1. Cylinders containing 150 liters of laser premix and 50 liter lecture bottles have both been used successfully. Use of an integrated valve/regulator assembly and 1/16" delivery lines allows connection of the supply to the laser without need for auxiliary purge tees, purge gases, traps, or vacuum pumps. Connecting of the supply to the laser is a simple operation similar to fueling of a portable camping stove.

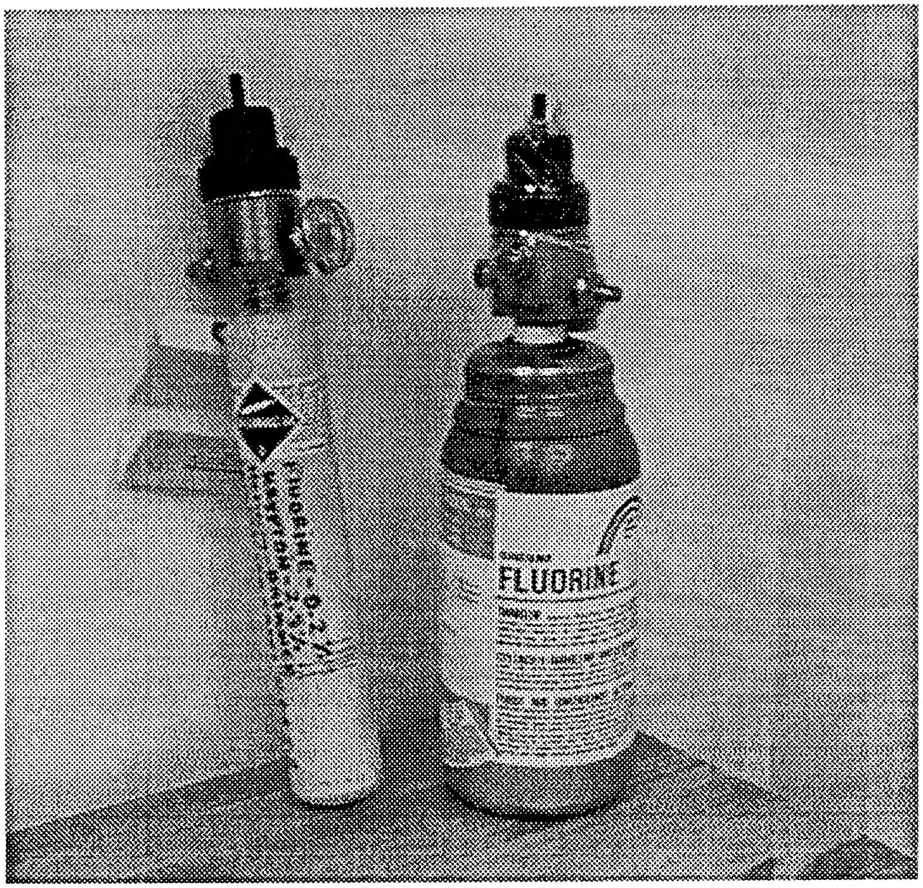

Fig. 1. Integrated valve regulator mounted on a 150 std-liter supply cylinder and on a lecture bottle.

III. DEVELOPMENT OF A COMPACT 250 mW ArF LASER.

A. Laser Design

1. General Considerations.

To avoid energy scaling limitations of ArF waveguide lasers and their sensitivity to oxygen impurities, we have used a more conventional pulsed dc discharge configuration.

The goals of the project were relatively unchanged, except that our average power target levels were raised. The revised project objectives were:

1. Development of a small ArF laser capable of 250 mW of average power at pulse repetition rates high enough to be suitable for micromachining and surgical applications (at least 100 Hz).

2. Development of a miniaturized gas supply for use with the laser.

3. Demonstration of lifetimes compatible with micromachining and surgical applications.

4. Design for low cost manufacturing.

It is well known that excimer lasers with pulsed dc excitation can be scaled to pulse energies of several joules, and high-power excimer sources are available from several manufacturers. It is also well known that conventional excimer lasers are difficult to scale down. This is because single pass gain and extraction efficiency decrease as length is shortened, discharges exhibit more tendency toward inhomogeniety as electrode gaps decrease, and small gas handling components are not readily available. However, engineering problems aside, pulsed dc excitation technology clearly is capable of production of the desired average power level. In addition, the laser gas can be exchanged between pulses. This minimizes the effects of optical absorption by O_2F and O_2F_2 species, which exist for several hundred milliseconds after the excitation discharge.

Large ArF lasers with good efficiency operate with optical gain of 10 - 20%/cm and specific energy of 4-5 J/liter, and efficiency of 1 - 1.5%[1,2]. To achieve 250 mW of average power at a repetition rate of 100 Hz, an active volume of only 0.5 cm^3 could be sufficient. Our prototype design used a volume of approximately 1 cm^3 (2.5mm x 2.5 mm x 15 cm) in order to assure that energy goals would be reached.

Most discharge-excited excimers of conventional design use an excitation circuit like that shown in Fig. 2. Energy in storage capacitor, C_1, is transferred to peaking capacitor, C_2, which is connected to the discharge region with a fast, low-inductance circuit. Discharge stability in a small gap excimer requires a faster transfer of energy from the peaking capacitor, C_2, to the discharge and a very low inductance, L_2, of the discharge head.

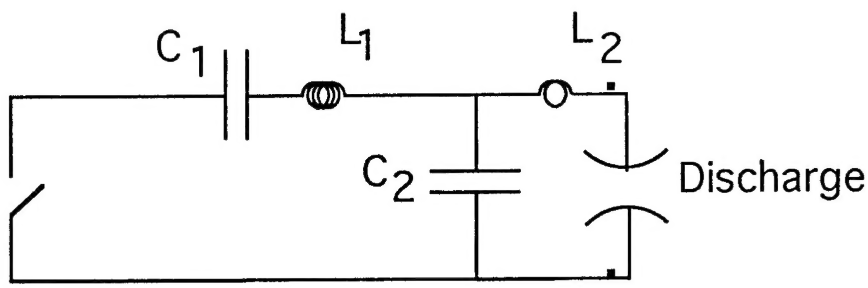

Fig. 2. Excimer laser discharge circuit.

To achieve the low inductance necessary for fast excitation of the small volume excimer we have used a circuit in which strontium titanate slabs with dielectric constant of approximately 500 are placed between conductive sheets to form a transmission line structure with a very low characteristic impedance. The cross-section of this structure is shown in Figure 3. Testing of the structure has shown that the strontium titanate material passivates on exposure to fluorine, in a manner similar to alumina or zirconia. The entire structure can be quite gas compatible when aluminum or brass are used for conductors.

The high dielectric constant of $SrTiO_3$ lowers the threshold for corona formation at interfaces with conductive corners of small radius. Several groups have shown that this

type of surface corona discharge can be used for laser preionization[3,4]. The corona is automatically synchronized with the charging of the transmission line and is most intense just before self-breakdown of the main discharge gap. Thus the configuration of Figure 3 has the combined benefits of simplicity, gas compatibility, and automatic synchronization of preionization.

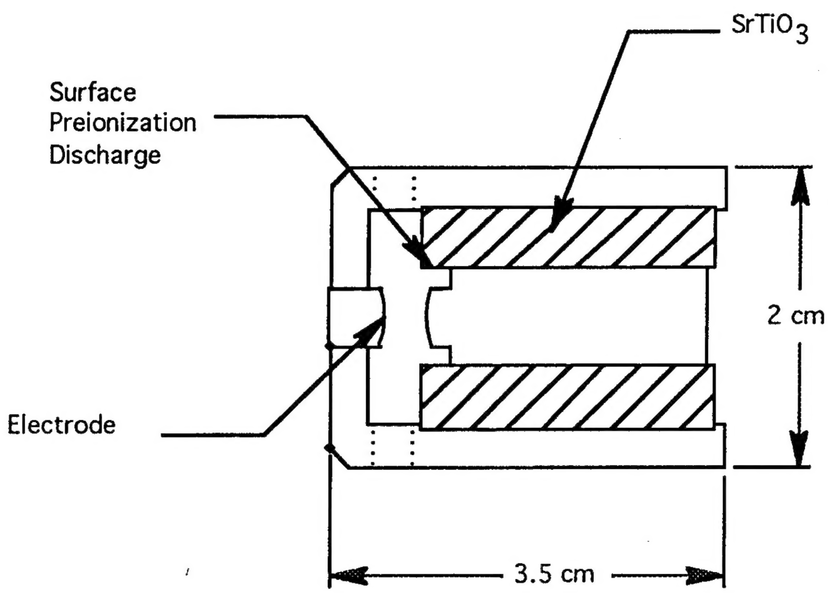

Fig. 2. Low inductance circuit for small ArF laser that allows very fast delivery of energy to the discharge region.

Production of high pulse repetition rates requires exchange of gas in the discharge gap between pulses. In large excimer lasers a fan or blower is used to circulate gas through the discharge region. The blower often resembles a squirrel-cage assembly driven by a motor outside the gas enclosure. Design of gas compatible components is complicated and failure of bearings and mechanical feedthroughs is not unusual. Scaling down conventional technology would require development of miniature fans,

drivers, seals, and other components to produce an assembly that is still likely to be a major cause of failure.

Since small excimer lasers require smaller volumetric flow rates to produce the necessary gas exchange, alternatives to conventional blowers can be considered. A promising alternative is based on electrohydrodynamic (EHD) effects in which an electric field acts on a partially ionized gas to generate flow. EHD flow effects have been studied since the turn of the century[5,6]. They have been shown to play a major role in electrostatic precepitators and to be potentially useful in enhancing convective heat transfer. Several Russian groups recently have investigated EHD gas circulation in lasers and shown the potential of the technique for small devices[7,8,9].

PPI has developed a proprietary EHD fan for application in small excimer lasers. The device has no moving parts, can be fabricated from gas compatible metal and ceramic components, and is capable of moving small volumes of laser gas at speeds as high as several meters per second. The EHD fan operates from a high voltage dc supply and consumes less than 10 watts of power.

Figure 4 shows an end view of a laser configuration that has produced a pulse energy of 3 mJ at pulse repetition rates of 100 Hz. The discharge section is mounted in an aluminum cylinder with an EHD fan to induce gas flow. There are no moving parts in the structure. The cylindrical enclosure is 4 inches in diameter and 8 inches long, so that the entire structure is very compact.

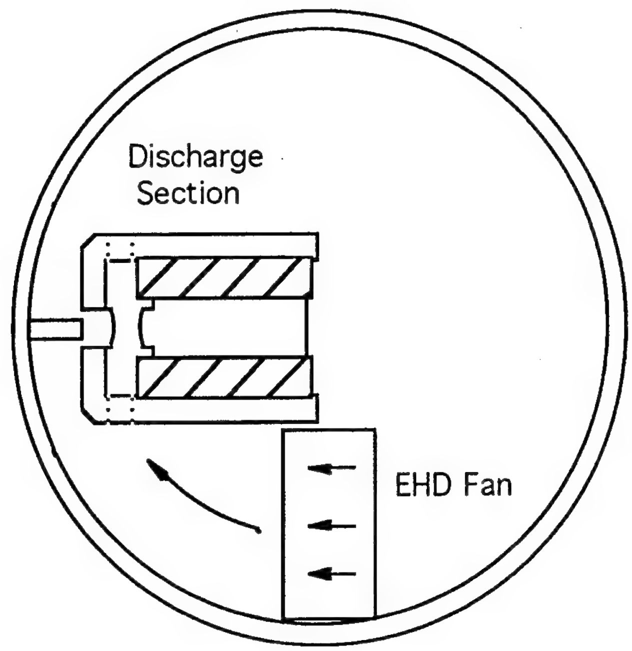

Fig. 4. Cross-section of ArF laser showing gas flow path.

The laser output beam has a cross-section of 2 mm x 3 mm and a divergence of about 2 milliradians. Pulse energy as a function of pulse repetition rate and an indication of static fill lifetime is shown in Fig. 5. Laser energy is relatively independent of pulse repetition rate over the 0 - 100 Hz range.

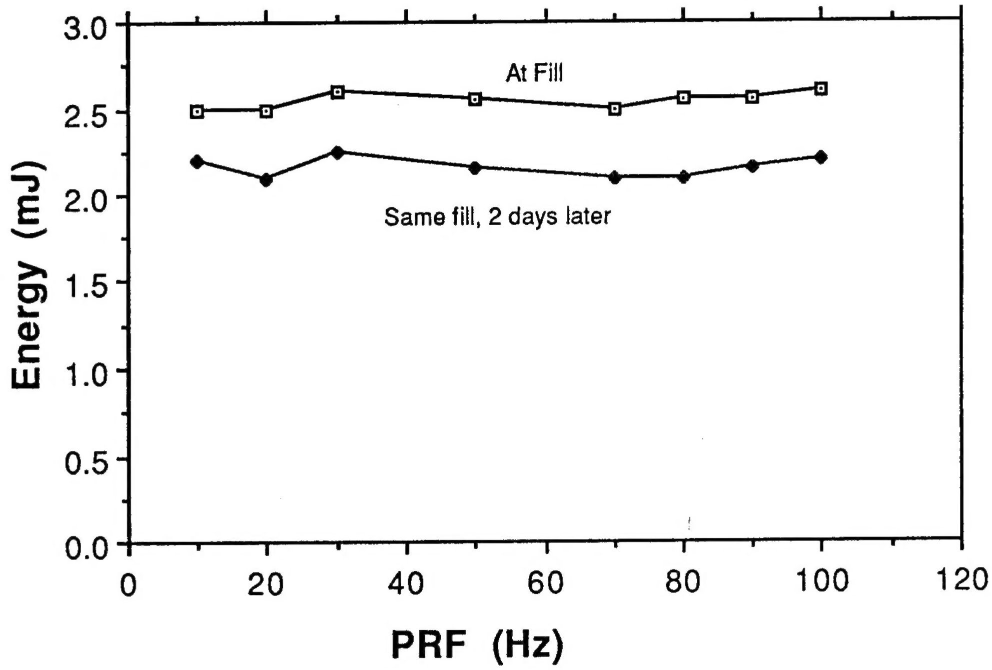

Fig. 5. Pulse energy as a function of pulse repetition rate for the small ArF laser. After two days without excitation, the same gas fill produced about 80% of the original energy.

The optimum laser gas mixture has been found to be 0.15% F_2, 5% Ar, balance Ne at a fill pressure of 90 psig. Approximately 10 std liters of premix are required to fill the discharge chamber, and each gas fill can produce about 3 x 10^5 pulses to half power. Static fill life of the ArF laser gas is typically several days. Although this is adequate for most applications, work will be undertaken in Phase III to improve both static and dynamic fill lifetimes, since this will further reduce operating costs and facility requirements for the laser.

Bercause of its relatively high operating pressure, the gas mixture can be exchanged by exhausting the spent premix to atmospheric pressure and refilling from a premix cylinder. A vacuum pump is not essential to operation, and full pumpout of the spent premix before refill increases output energy by less than 10%. Gas refills can be made on an as needed basis

or a slow continuous flow can be used for gas exchange. With its current life characteristics, approximately 10 liters of premix per hour are required when the laser is operating at maximum repetition rate. Gas costs in the worst case are approximately $5/hour.

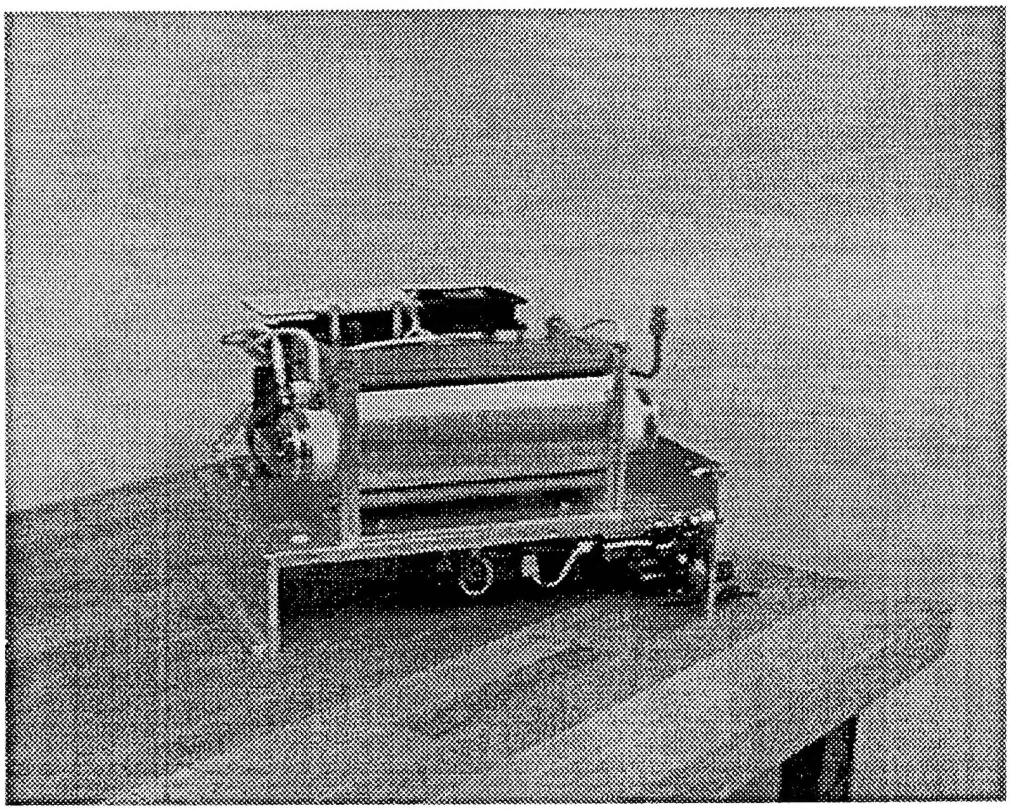

Fig.6. Photograph of miniature ArF laser prototype.

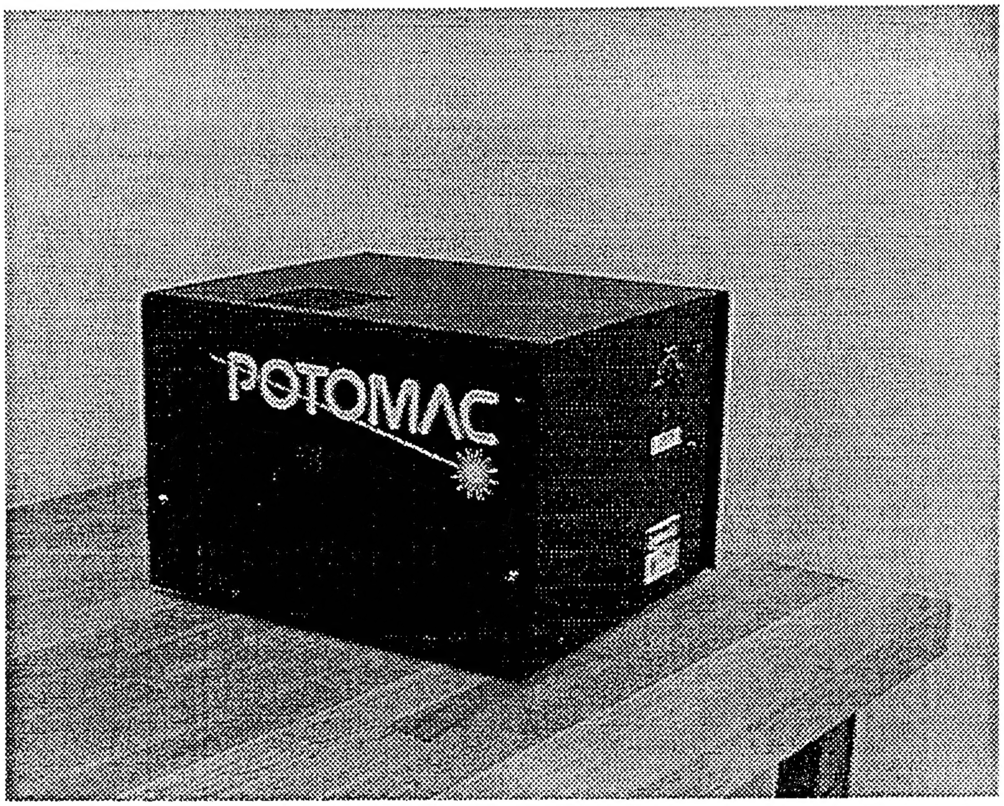

Fig.7. Photograph of miniature ArF laser in enclosure.

IV. PHASE III

The new laser described in the above paragraphs produces enough average power to carry out a photorefractive keratectomy (PRK) procedure is less than 10 minutes. We have received a $500K laser development contract from a new company developing a PRK instrument that will be dramatically smaller and less expensive than currently available units. The new instrument incorporates an eye tracking technique to allow use of a small focused ArF laser which is scanned over the cornea to produce the desired lens pattern.

We also have integrated the laser into our micromachining system and will ship our first unit-- for application in integrated optics device development -- in spring of 1995.

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